

Contract # N00014-14-C-0004

Autonomous Control Modes and Optimized Path Guidance for Shipboard Landing in High Sea States

Progress Report (CDRL A001)

Progress Report for Period: October 10, 2015 to January 9, 2016

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Section I: Project Summary

1. Overview of Project

This project is performed under the Office of Naval Research program on Basic and Applied Research in Sea-Based Aviation (ONR BAA12-SN-0028). This project addresses the Sea Based Aviation (SBA) initiative in Advanced Handling Qualities for Rotorcraft.

Landing a rotorcraft on a moving ship deck and under the influence of the unsteady ship airwake is extremely challenging. In high sea states, gusty conditions, and a degraded visual environment, workload during the landing task begins to approach the limits of a human pilot's capability. It is a similarly demanding task for shipboard launch and recovery of a VTOL UAV. There is a clear need for additional levels of stability and control augmentation and, ultimately, fully autonomous landing (possibly with manual pilot control as a back-up mode for piloted flight). There is also a clear need for advanced flight controls to expand the operational conditions in which safe landings for both manned and unmanned rotorcraft can be performed. For piloted rotorcraft, the current piloting strategies do not even make use of the available couplers and autopilot systems during landing operations. One of the reasons is that, as the deck pitches and rolls in high sea states, the pilot must maneuver aggressively to perform a station-keeping task over the landing spot. The required maneuvering can easily saturate an autopilot that uses a rate limited trim system. For fly-by-wire aircraft, there is evidence that the pilot would simply over-compensate and negate the effectiveness of a translation rate command/position hold control mode. In addition, the pilots can easily over-torque the rotorcraft, especially if they attempt to match the vertical motion of the deck.

This project seeks to develop advanced control law frameworks and design methodologies to provide autonomous landing (or, alternatively, a high level of control augmentation for pilot-in-the-loop landings). The design framework will focus on some of the most critical components of autonomous landing control laws with the objective of improving safety and expanding the operational capability of manned and unmanned rotorcraft. The key components include approach path planning that allows for a maneuvering ship, high performance station-keeping and gust rejection over a landing deck in high winds/sea states, and deck motion feedback algorithms to allow for improved tracking of the desired landing position and timing of final descent.

2. Activities this period

Task 11 – Control Parameter Optimization

During this reporting period, efforts were made to develop a method for finding optimized control parameters to enhance the path tracking performance. As a preliminary study, the inner-loop feedback control system (attitude control) was considered (Figure 1). The optimization method used in this study was KSOPT (Kreisselmeier-Steinhauser OPTimizer). The KS function combines multiple objective functions with the constraints to form a single composite function (KS function), which can, in turn, be optimized by using unconstrained optimization techniques. The KS function was first used by Kreisselmeier and Steinhauser and is defined as

$$K(\vec{x}) = \frac{1}{\rho} \ln \sum_{m=1}^M e^{\rho F_m(\vec{x})}$$

Where ρ is a scalar multiplying factor used in the KS function and $F_m(\vec{x})$ is a set of M functions, which, in the current context, are the objective functions and the constraints. To convert the original constrained optimization problem to an unconstrained optimization problem, the KS function combines the objective functions with the constraint functions into a single composite function. This unconstrained KSOPT has been incorporated into FLIGHTLAB as a general purpose constrained minimization component.

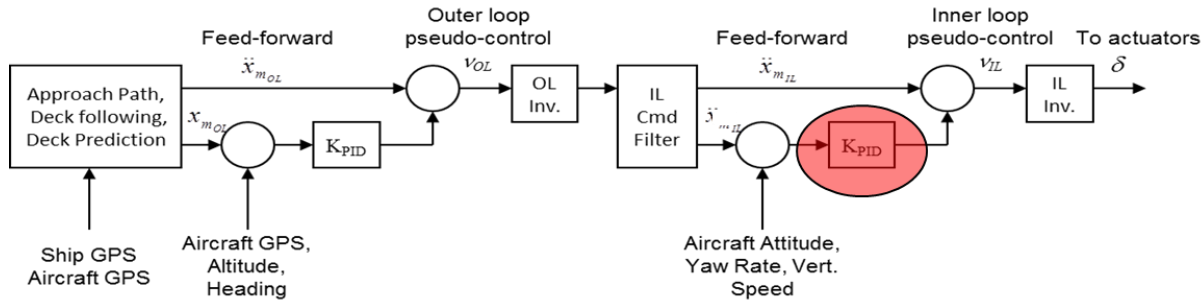


Figure 1 Dynamic inversion control system

The KSOPT component was written using a modular approach which allows portions of a component to be easily replaced as new and improved methods are developed. It should be noted that the user must provide the appropriate function to evaluate the desired costs and constraints for the optimizer. Once all the required information is determined, the optimization problem is then initialized to allocate space for internal arrays and to test the initial design variables. The KSOPT component is then called in a loop with the user supplied analysis procedures until the optimization problem is solved. At each iteration, the initial function value and the derivatives of the KS function are obtained from the function values/derivatives of the objective functions and constraint functions supplied by the user. After forming the composite KS function value and gradient with respect to the design variable, an unconstrained optimization problem related to the KS function is defined and can be solved iteratively. This unconstrained problem is solved by first finding a search direction vector using the Davidon-Fletcher-Powell (DFP) algorithm. The above implementation of the unconstrained optimization procedure treats the side constraints on the design variables separately from the other general constraints since it is sometimes desirable to approach the side constraints as closely as possible without violating them. Forming the side constraints on the design variables in the same way as the general constraints will not allow the optimization to approach the side constraint closely. Therefore, in the KSOPT method, the side constraints are inherently tackled inside the one dimensional line search procedure described above.

The proposed optimization process has been tested using the light weight class helicopter model with the SCONE2 ship motion. The inner loop feedback controller consists of a total of 10 gains (Lateral: 3 gains, Longitudinal: 3 gains, Collective: 2 gains, and Pedal: 2 gains) to be tuned. Four tracking errors (roll, pitch, yaw, and vertical speed) were assigned as an objective function for each channel. It should be noted that each channel is assumed to be independent during the optimization process. Thus, the calculation of the objective's gradient is slightly modified to remove any cross-coupling effects among the control channels. The objective functions are formed as the sum of squared tracking error for faster convergence.

Figures 2–5 show some representative simulation results with the optimized gains for an approach and stationkeeping maneuver. The results show overall behavior and performance was similar to the simulation with the original gain set. The original gain set showed reasonably good tracking performance, so this is not that surprising. However, one noticeable difference is the reduction of overshoot in the vertical axis (heave) channel when the controller arrests the descent and forward relative speed (Figure 3). The optimized gains result in near perfect tracking of the altitude profile, whereas the original gains resulted in significant overshoots of descent rate and perhaps dangerously low altitude over the deck. It is hypothesized that the KS cost function for the inner loop feedback controller is dominated by the heave-axis error because the attitude error is relatively smaller than position error. In addition, the heave-axis was the one axis in which the controller showed poor performance for certain approach maneuvers.

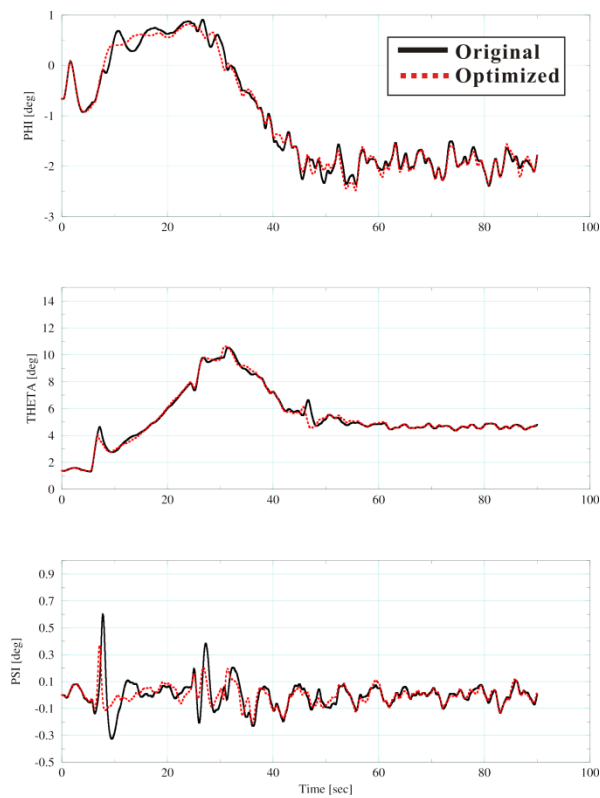


Figure 2 Aircraft attitude

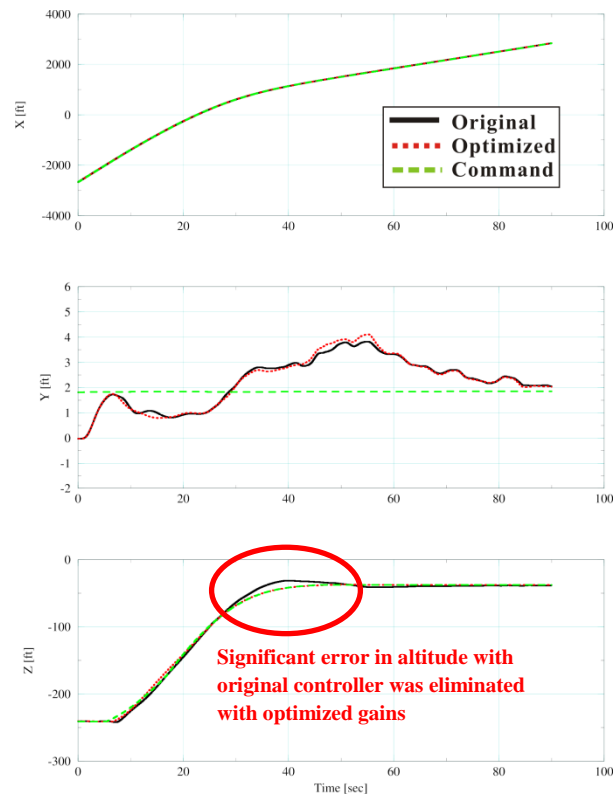


Figure 3 Aircraft position

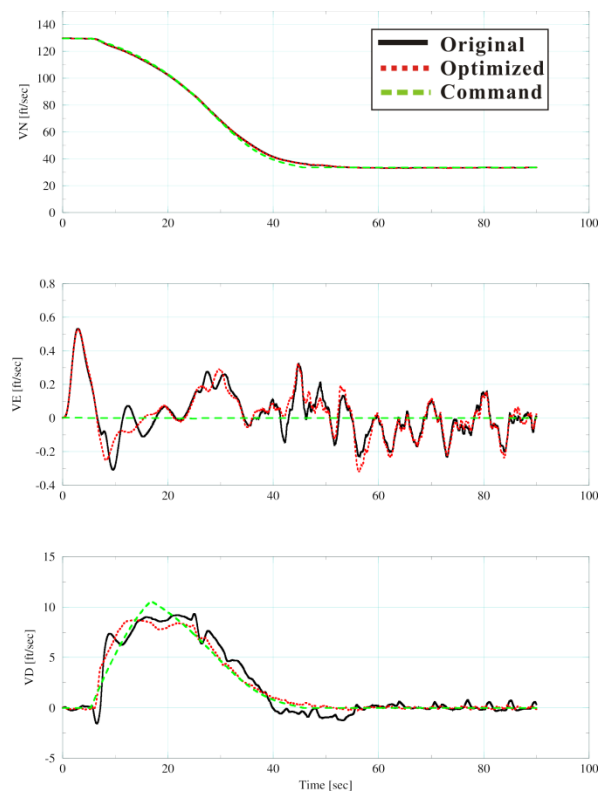


Figure 4 Aircraft velocity

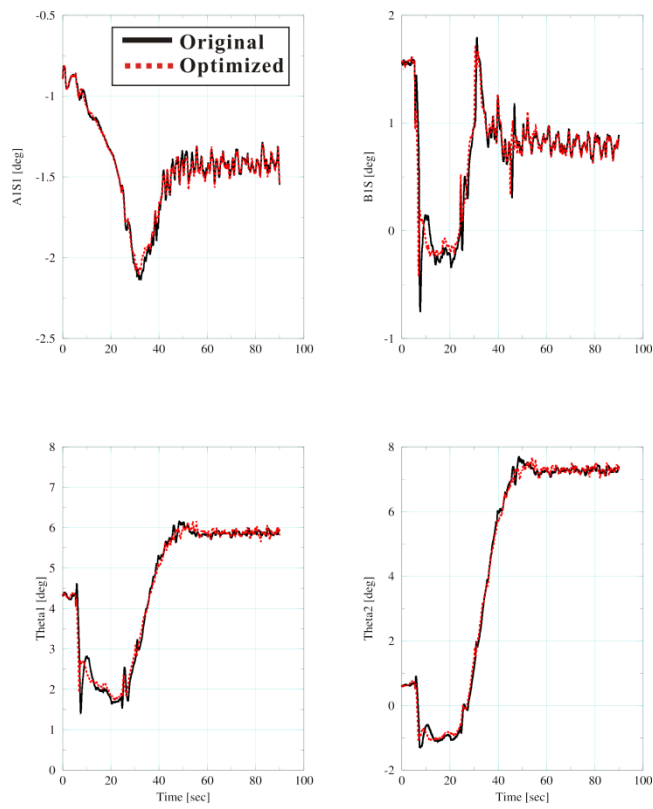


Figure 5 Swashplates control inputs

Task 6 and Task 12 Path Optimization

The ship-relative path generation algorithms have been extended to allow curved approach paths. This approach expresses the approach path in terms of a B-spline, and the final shape of the trajectory can be obtained by optimization methods, with various criteria integrated into the optimization objective function. Such an algorithm might allow non-standard curved approach paths or even adaptable approach paths to accommodate a maneuvering ship or varying environmental condition. A trackable flight path can be derived to include desirable properties such as:

1. Initial path direction matches current flight direction as close as possible. This condition defines the initial Flight Path Angle in the vertical plane, and initial Flight Heading Angle in the horizontal plane.
2. The terminal path direction matches the specified approach angle and heading. This condition could then evolve into criteria with respect to approaching azimuth and glide slope angles ψ_{app} and γ_{app} .
3. The path length can be minimized in the optimization.
4. Path curvature should be within constraints defined by the helicopter maneuverability, meanwhile the variation of path curvature is to be as little as possible to avoid unnecessary maneuvering.

Other criteria will be studied in the future work, but Figure 6– Figure 9 show the flexibility of this method in path generation. The parameters are defined in the ship heading frame, and for all of the cases shown, the relative x, y, z positions are defined by: XPOS=-1700 ft, YPOS=-1000 ft, ZPOS=-283 ft. For each case, there are variations in the initial Flight Path Angle (FPA), initial Flight Heading Angle (FHA), final approach azimuth ψ_{app} , and final approach glide slope γ_{app} .

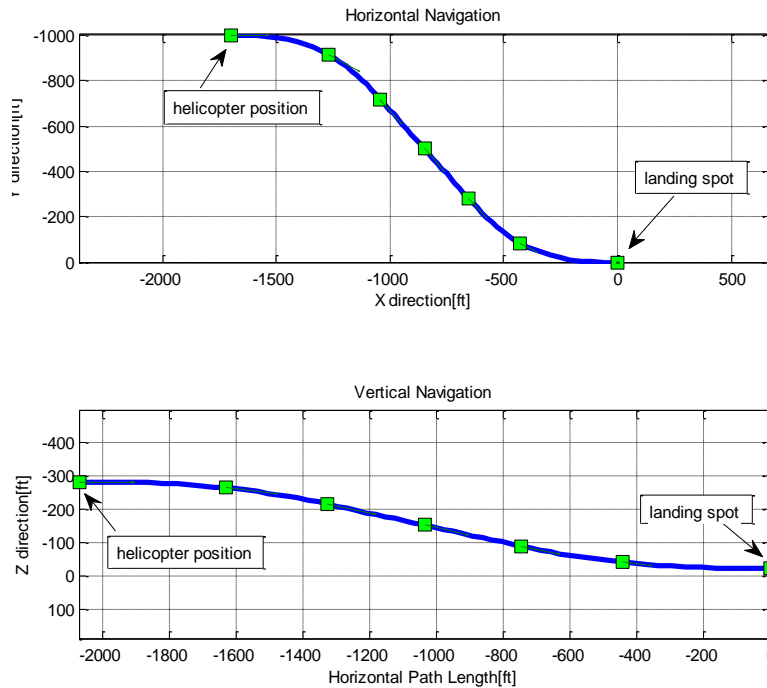


Figure 6. FHA=0 deg, FPA=0 deg, $\psi_{app}=0$, $\gamma_{app}=0$

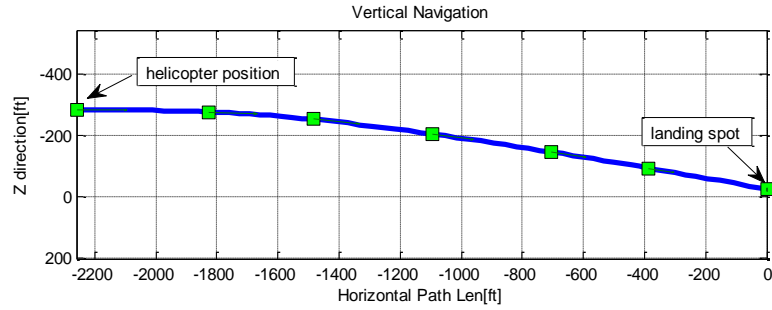
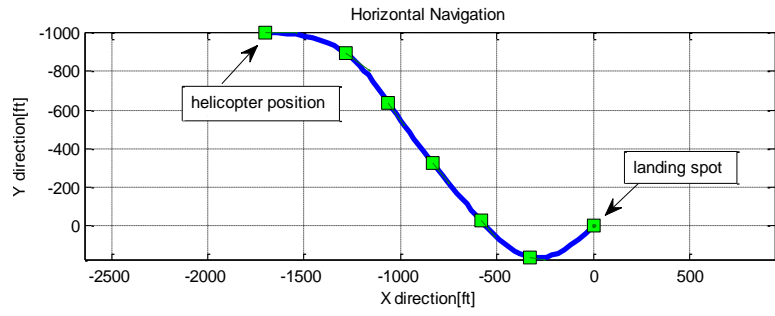


Figure 7. $FHA=0$ deg, $FPA=0$ deg, $\psi_{app}=-45$ deg, $\gamma_{app}=10$ deg

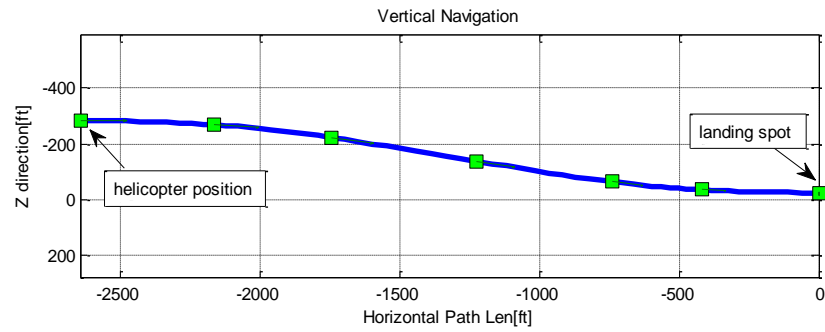
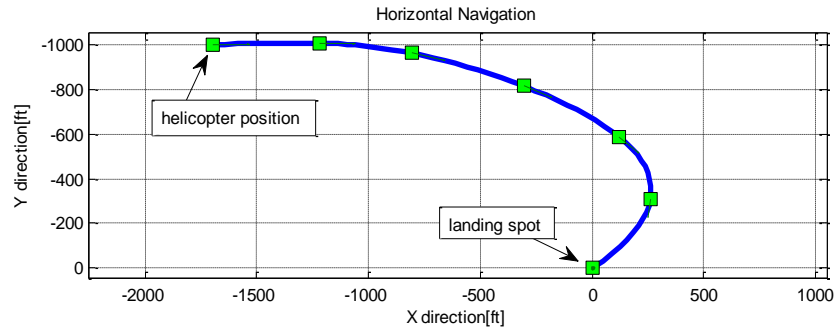


Figure 8. $FHA=0$ deg, $FPA=0$ deg, $\psi_{app}=145$ deg, $\gamma_{app}=0$ deg

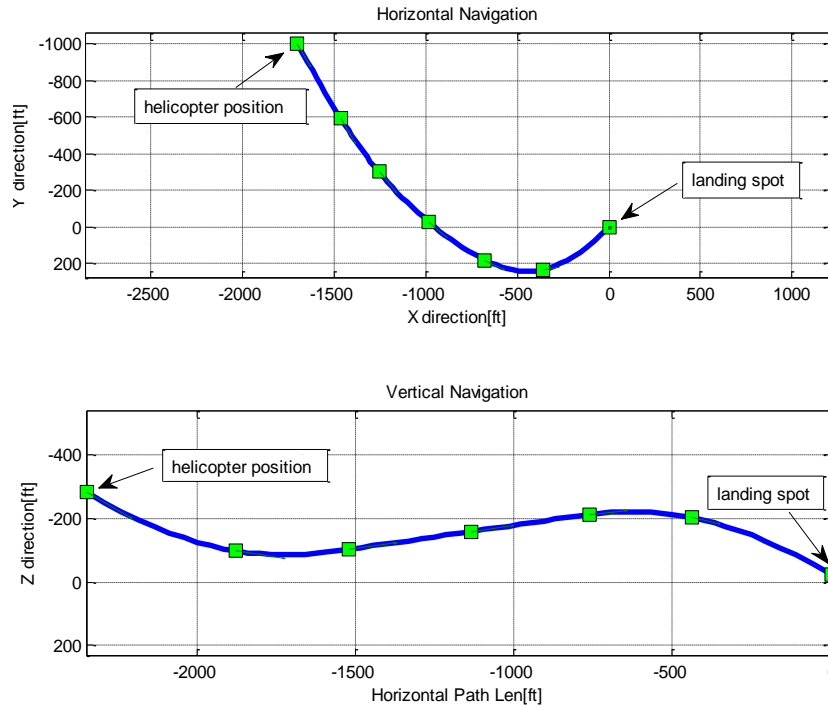


Figure 9. FHA=60 deg, FPA=-45 deg, $\psi_{app} = -30$ deg, $\gamma_{app} = -30$ deg

3. Significance of Results

A preliminary optimization process was applied to find the optimal control parameters to improve overall approach and stationkeeping maneuver for a light weight class helicopter model. Anticipated performance is obtained to enhance the inner loop control system. Noticeable improvement was observed primarily in the heave axis. The original control gains were resulted in relatively small attitude errors, so there was minimal room for improvement, but the altitude tracking, especially in aggressive approaches, could be improved significantly with the gain optimizations.

The feasibility of applying B-spline path representations for curved and adaptive approach paths was investigated. Results demonstrated great potential of this method in generating paths from different initial and final approach angles. The nature of the parameterization allows us to incorporate various criteria into path optimization. The method might allow for adaptive approach path optimization for a maneuvering ship or for changing environmental conditions.

4. Plans and upcoming events for next reporting period

Control Law Development: In the next reporting period, we will continue to make progress on control laws through Task 8 *Station Keeping Control Laws*, Task 9 *Vertical Axis Control Laws*, Task 10 *Gust Rejection Control Laws*, and Task 11 *Optimization of Control Parameters*. All of these components are integrated with the DI control architecture. Tasks 8, 9, and 10 have been at least partially addressed in year one of the program, and we continue to make incremental progress in refining the control laws for both approach and landing.

We will continue to develop novel control schemes for the station-keeping and landing phase, building on the optimal control method with deck motion prediction as presented in the ERF paper. For the vertical axis, we will bring in the issues of torque and control margin limits for the helicopter operating at high gross weights.

ART will integrate the control law updates for the generic heavy/medium/light weight class helicopters to provide our research team a consistent and unified model and analysis utilities to expedite further development. Configuration control is a challenge given the numerous members of the team at PSU, ART, NAVAIR, and NSWCCD.

Path Optimization: We will investigate the inclusion of additional performance metrics (i.e., actuator margins) as well as varied weightings between the performance factors. The B-spline type path generation algorithm will be integrated into the simulation environment in FLIGHTLAB to verify the tracking performance of designed controller. We plan to apply the KSOpt tool for on-line path optimization (in addition to using it for control gain optimization).

Control Parameter Optimization: The optimization scheme will be expanded to include the outer loop controller and path optimization. The cost functions and the constraints will be carefully selected in order to find the optimal gains of the proposed control system. The parameters of the command filter will also be considered for optimization. The resulting set of advanced control laws with optimal gains and filter parameters will be integrated into the flight dynamics model using CSGE in FLIGHTLAB.

5. References

None

6. Transitions/Impact

We continue to transition our models and control laws to counterparts at NAVAIR and NSWCCD (Sean Roark and Al Schwarz), and to John Tritschler (now at USNTPS).

7. Collaborations

Penn State and ART have collaborated directly with John Tritschler and Sean Roark at NAVAIR. In addition, we are communicating with other Navy researchers pursuing similar projects: Al Schwarz at NSWCCD and Dave Findlay at NAVAIR.

8. Personnel supported

Principal investigator: Joseph F. Horn

Graduate Students: Junfeng Yang, PhD Candidate

9. Publications

Tritschler J.K., Horn J.F., and He, C. "Objective Function Development for Optimized Path Guidance for Rotorcraft Shipboard Recovery". AIAA Atmospheric Flight Mechanics Conference, Dallas TX, June 22-26 2015.

Horn J.F., Yang, J.F., He, C., Lee, D., and Tritschler, J.K. "Autonomous Ship Approach and Landing using a Dynamic Inversion Control with Deck Motion Prediction." 2015 European Rotorcraft Forum in Munich Germany, September 1-3, 2015

10. Point of Contact in Navy

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Section II: Project Metrics

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Advanced Rotorcraft
Technologies

January 29, 2016

1. Metrics

Number of faculty supported under this project during this reporting period: 1

Number of post-doctoral researchers supported under this project during this period: 0

Number of graduate students supported under this project during this reporting period: 1

Number of undergraduate students supported under this project during this period: 0

Number of refereed publications during this reporting period for which at least 1/3 of the work was done under this effort: 0

Number of publications (all) during this reporting period: 0

Number of patents during this reporting period: 0

Number of M.S. students graduated during this reporting period: 0

Number of Ph.D. students graduated during this reporting period: 0

Awards received during this reporting period: 0

Invited talks given: 0

Conferences at which presentations were given (not including invited talks above): 2